The Effects of Resonant Tunneling on Magnetoresistance through a Quantum Dot

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Abstract

The effect of resonant tunneling on magnetoresistance (MR) is studied theoretically in a double junction system. We have found that the ratio of the MR of the resonant peak current is reduced more than that of the single junction, whereas that of the valley current is enhanced depending on the change of the discrete energy-level under the change of magnetic field. We also found that the peak current-valley current (PV) ratio decreases when the junction conductance increases.

I. INTRODUCTION

As nano-fabrication technology using magnetic materials advances, the magnetoresistance (MR) in mesoscopic systems has attracted growing interest, mainly because of its possible applications in storage devices [1,2]. The resonant tunneling phenomenon is one of the events expected to occur in magnetic nano-particles or thin film systems where discrete energy-level structures are prominent. Ferromagnet/insulator/ferromagnet/insulator/ferromagnet (FM/I/FM/I/FM) is a basic structure of this system. The electron tunneling through the insulator is considered to be based on the independent polarized electrons and the difference in MR is considered to be derived from the difference of the spin polarized free electron tunneling [3,4]. Recently, Zhang *et al.* [5]

calculated the I-V characteristics of the FM/I/FM/I/FM structure based on the Tsu-Esaki formulation (S-matrix theory) and showed that the MR is more than 90%, which is a great enhancement compared with the case of a single junction . However, the origin of the enhancement is not clear. In addition, although the peak current-valley current (PV) ratio is one of the key factors of resonant tunneling, the effect of the MR on this ratio has not been clarified. This is because S-matrix theory is not easily applied to analyze the underlying physics, in spite of its usefulness as a more realistic method for self-consistent calculations. In this paper we discuss the effects of the resonant tunneling on the MR *analytically*, based on the two band spin polarized free electron model. We assume that the capacitances of two junctions are large and neglect charging effects. The general formula of current-voltage characteristics is obtained by elaborating that derived by Jauho *et al.* [6] and is shown to be a useful formula for investigating the detailed physics of a double barrier structure. As we are using Green's function method, our model can be extended, by refining the self-energy part of Green functions, to be applied to the case in which free electron approximation cannot be used because of the existence of some scatterings, although it is not the subject of this paper.

II. FORMULATION OF THE DESCRIPTION OF THE SYSTEM

The Hamiltonian consists of the electronic part $\hat{H}_{\rm E}$, and the transfer part $\hat{H}_{\rm T}$. The electronic part consists of electrode and island parts,

$$\hat{H}_{\rm E} = \sum_{\mathbf{k},\alpha\in L,R,\sigma} E_{\mathbf{k}\alpha\sigma}\hat{c}^{\dagger}_{\mathbf{k}\alpha\sigma}\hat{c}_{\mathbf{k}\alpha\sigma} + \sum_{m\sigma} E_{m\sigma}\hat{d}^{\dagger}_{m\sigma}\hat{d}_{m\sigma}, \tag{1}$$

where α represents a set of parameters that, together with wave vectors $\mathbf{k}$, completely specify the electronic state of the left (L) or right (R) electrode, and m specifies the energy levels of the central island. By an internal magnetic field $\mathbf{h}_\alpha$ and with the Pauli spin matrix σ, the energy dispersion relation is expressed as [4,5]

$$E_{\mathbf{k}\alpha\sigma} = \hbar^2\mathbf{k}^2_\sigma/(2m) - \mathbf{h}_\alpha\cdot\sigma. \tag{2}$$

Hereafter we write $E_{\mathbf{k}\alpha\uparrow} = \hbar^2\mathbf{k}_\uparrow^2/(2m) - h_\alpha$ and $E_{\mathbf{k}\alpha\downarrow} = \hbar^2\mathbf{k}_\downarrow^2/(2m) + h_\alpha$. The transfer part is described by

$$\hat{H}_{\mathrm{T}} = \sum_{n\mathbf{k}\alpha\in L,R\sigma} [V_{n\mathbf{k}\alpha\sigma}(t)\hat{c}^\dagger_{\mathbf{k}\alpha\sigma}\hat{d}_{n\sigma} + \mathrm{h.c.}]. \tag{3}$$

The current at junction α (=L or R) is given by [6,7]

$$\begin{aligned} J_\alpha(t) &= (-)^\beta e\sum_\sigma \langle \dot{\hat{N}}_{\alpha\sigma}\rangle = -(-)^\beta \frac{ie}{\hbar}\sum_\sigma \langle[\hat{H}, \hat{N}_{\alpha\sigma}]\rangle \\ &= (-)^\beta \frac{ie}{\hbar}\sum_{n\mathbf{k}\sigma}[V_{n\mathbf{k}\alpha\sigma}\langle \hat{c}^\dagger_{\mathbf{k}\alpha\sigma}\hat{d}_{n\sigma}\rangle - V^*_{n\mathbf{k}\alpha\sigma}\langle \hat{d}^\dagger_{n\sigma}\hat{c}_{\mathbf{k}\alpha\sigma}\rangle] \\ &= (-)^\beta \frac{2e}{\hbar}\mathrm{Re}\left\{\sum_{\mathbf{k}n\sigma} V_{n\mathbf{k}\alpha\sigma}(t) G^<_{n\mathbf{k}\alpha\sigma}(t,t)\right\}, \end{aligned} \tag{4}$$

where β=0 for the left junction and β=1 for the right junction and $G^<_{n\mathbf{k}\alpha\sigma}(t,t') \equiv i\langle \hat{c}^\dagger_{\mathbf{k}\alpha\sigma}(t)\hat{d}_{n\sigma}(t')\rangle$ is an analytic continuation of the contour-ordered Green's function $G^<_{n\mathbf{k}\alpha\sigma}(\tau,\tau')$ which is defined in the interaction representation by

$$\begin{aligned} G_{n\mathbf{k}\alpha\sigma}(\tau,\tau') \equiv\, & i\langle T_C\{\hat{c}^\dagger_{\mathbf{k}\alpha\sigma}(\tau')\hat{d}_{n\sigma}(\tau) \\ & \times \exp\left(-\frac{i}{\hbar}\int_C \hat{H}_{\mathrm{T}}(\tau_1)d\tau_1\right)\}\rangle, \end{aligned} \tag{5}$$

where T_C is the contour-ordering operator. We assume that electrons in the left and right electrodes are noninteracting. Then the only nonvanishing terms in Eq. (5) are those in which $\hat{c}^\dagger_{\mathbf{k}\alpha}(\tau')$ is contracted with $\hat{c}_{\mathbf{k}\alpha}(\tau_1)$ in the exponential term. We then obtain, after analytic continuation to real time,

$$\begin{aligned} G^<_{n\mathbf{k}\alpha\sigma}(t,t') =& \sum_m \int_{-\infty}^{\infty}\frac{dt_1}{\hbar} V^*_{n\mathbf{k}\alpha\sigma}(t_1)[G^r_{nm\sigma}(t,t_1)g^<_{\mathbf{k}\alpha\sigma}(t_1,t') \\ & + G^<_{nm\sigma}(t,t_1)g^a_{\mathbf{k}\alpha\sigma}(t_1,t')], \end{aligned} \tag{6}$$

where $G^<_{nm\sigma}(t,t') \equiv i\langle \hat{d}^\dagger_{m\sigma}(t')\hat{d}_{n\sigma}(t)\rangle$ is the Green's function of the central island, and

$$g^<_{\mathbf{k}\alpha\sigma}(t_1,t_2) \equiv i\langle \hat{c}^\dagger_{\mathbf{k}\alpha\sigma}(t_2)\hat{c}_{\mathbf{k}\alpha}(t_1)\rangle, \tag{7}$$

$$g^>_{\mathbf{k}\alpha\sigma}(t_1,t_2) \equiv -i\langle \hat{c}_{\mathbf{k}\alpha\sigma}(t_1)\hat{c}^\dagger_{\mathbf{k}\alpha\sigma}(t_2)\rangle. \tag{8}$$

Substituting Eq. (6) into Eq. (4), we obtain

$$J_\alpha(t) = (-1)^\beta \frac{e}{\hbar^2} \sum_{\mathbf{k}mn\sigma} V_{n\mathbf{k}\alpha\sigma}(t) \int_{-\infty}^{\infty} dt' V^*_{m\mathbf{k}\alpha\sigma}(t') \{ G^>_{nm\sigma}(t,t') \times g^<_{\mathbf{k}\alpha\sigma}(t',t) - G^<_{nm\sigma}(t,t') g^>_{\mathbf{k}\alpha\sigma}(t',t) \}, \tag{9}$$

where $G^>_{nm\sigma}(t,t') \equiv -i\langle \hat{d}_{n\sigma}(t)\hat{d}^\dagger_{m\sigma}(t')\rangle$. By introducing a noninteracting self-energy, $\Sigma_0^{><}$, defined by $G_0^{><} = G_0^r \Sigma_0^{><} G_0^a$, and using the Dyson equations, $(1 + G^r\Sigma^r)G_0^r = G^r$ and $G_0^a(1+\Sigma^a G^a) = G^a$, we may cast the Keldysh equation $G^{><} = (1+G^r\Sigma^r)G_0^{><}(1+\Sigma^a G^a) + G^r \Sigma G^a$ into the following form [8]:

$$G^{><}_{nm\sigma}(t,t') = \sum_{n_1,n_2} \int dt_1 dt_2 G^r_{nn_1\sigma}(t,t_1) \Sigma^{><}_{\mathrm{tot}\ n_1 n_2 \sigma}(t_1,t_2) \times G^a_{n_2 m\sigma}(t_2,t'), \tag{10}$$

where

$$\Sigma^{><}_{\mathrm{tot}\ n_1 n_2\sigma}(t_1,t_2) = \Sigma^{><}_{0\ n_1n_2\sigma}(t_1,t_2) + \Sigma^{><}_{\mathrm{T}\ n_1n_2\sigma}(t_1,t_2) \tag{11}$$

The first term on the right-hand side describes the self-energy of the island in the absence of disorder, interaction, and tunneling. Since it corresponds to the free part, it is infinitesimal: $\Sigma^{><}_{0n_1n_2\sigma}(\epsilon) = 2i\delta_{n_1n_2}\eta[f_0(\epsilon) - 1/2 \mp 1/2]$, where η is a positive infinitesimal, $>$ ($<$) refers to the minus (plus) sign, $f_0(\epsilon) = (\exp\beta(\epsilon - V_d) + 1)^{-1}$, and V_d is the bottom of the island energy. The second term describes a self-energy due to tunneling:

$$\Sigma^{><}_{\mathrm{T}n_1n_2\sigma}(t_1,t_2) = \sum_{\mathbf{k}\alpha} \frac{V^*_{n_1\mathbf{k}\alpha\sigma}(t_1)V_{n_2\mathbf{k}\alpha\sigma}(t_2)}{\hbar^2} g^{><}_{\mathbf{k}\alpha\sigma}(t_1,t_2). \tag{12}$$

Because of the infinitesimal factor η, the free part is important only when the remaining parts are absent (it is not the present case).

In the following we focus on the case in which $\Gamma_{nn'\mathbf{k}\alpha\sigma}(t,t') \equiv 2\pi\ V^*_{n\mathbf{k}\alpha\sigma}(t)\ V_{n'\mathbf{k}\alpha\sigma}(t')$ is a real function of $t-t'$. From Eq. (9), J_L-J_R $= e\sum_\sigma \int_{-\infty}^{\infty} dt'\ (G^>_{nm\sigma}(t,t')\Sigma^<_{\mathrm{T}mn\sigma}(t',t) - G^<_{nm\sigma}(t,t')\Sigma^>_{\mathrm{T}mn\sigma}(t',t))$. Because $G^{><}_{nm\sigma}(t,t')$ contains $\Sigma^{><}_{\mathrm{T}mn\sigma}(t,t')$ (Eq. (12)), the conservation of current through the two junctions is automatically satisfied, that is, $J_L = J_R$. Thus we can discuss the current through the junctions by J_L.

The retarded and advanced Fourier-transformed Green's functions at the central island, $G^r_{nn'\sigma}(\epsilon)$ and $G^a_{nn'\sigma}(\epsilon)$, are derived from the Dyson equation:

$$\hbar[G^{r,a}_{nn'\sigma}(\epsilon)]^{-1} = \hbar[g^{r,a}_{n\sigma}(\epsilon)]^{-1} - \hbar\Sigma^{r,a}_{\text{tot}\ nn'\sigma}(\epsilon)$$
$$= \epsilon - (E_{n\sigma} + V_{d\sigma}) - \Lambda_{nn'\sigma}(\epsilon) \pm \frac{i}{2}\left(2\eta + \Gamma_{nn'\sigma}(\epsilon)\right), \tag{13}$$

where $\Gamma_{nn'\sigma}(\epsilon) \equiv 2\text{Im}\Sigma^a_{\text{T}nn'\sigma}(\epsilon)$, and $2\pi\hbar\Sigma^{r,a}_{\text{T}nn'\sigma}(\epsilon) = \sum_{\mathbf{k}\alpha}\Gamma_{nn'\mathbf{k}\alpha\sigma}(\epsilon)g^{r,a}_{\mathbf{k}\alpha\sigma}(\epsilon)$. The real part of the self-energy $\Lambda_{nn'\sigma}(\epsilon)$ shifts energy-levels in the central island and we will regard this effect as included in our assumed one-body energy levels of the quantum dot. Here $\Gamma_{nn'\sigma}(\epsilon)$ shows the half-width of resonant peaks :

$$\Gamma_{nn'\sigma}(\epsilon) = \sum_{\mathbf{k}\alpha}\int d\epsilon_1 \Gamma_{nn'\mathbf{k}\alpha}(\epsilon_1)\delta(\epsilon - \epsilon_1 - E_{\mathbf{k}\alpha\sigma}) \tag{14}$$

With $A_{n_1n_2\sigma}(\epsilon) \equiv i(G^r_{n_1n_2\sigma}(\epsilon) - G^a_{n_1n_2\sigma}(\epsilon))$, and $\hbar\Theta_{nm\sigma}(\epsilon) \equiv G^r_{nn_1\sigma}(\epsilon)G^a_{n_2m\sigma}(\epsilon)/A_{n_1n_2\sigma}(\epsilon)$, J_L can be cast into the following form,

$$J_L = \frac{e}{2\pi\hbar^2}\sum_{\substack{\mathbf{k}\mathbf{k}'nm\\ n_1n_2\sigma}}\int_{-\infty}^{\infty} d\epsilon \Gamma^*_{nm\mathbf{k}L\sigma}(\epsilon)\Gamma^*_{n_1n_2\mathbf{k}'R\sigma}(\epsilon)A_{n_1n_2\sigma}(\epsilon)$$
$$\times\Theta_{nm\sigma}(\epsilon)\{f_L(E_{\mathbf{k}L\sigma}) - f_R(E_{\mathbf{k}'R\sigma})\}\delta(\epsilon - E_{\mathbf{k}L\sigma})\delta(\epsilon - E_{\mathbf{k}'R\sigma}). \tag{15}$$

This is a general expression of current where $f_L(\epsilon) = 1/(e^{\beta(\epsilon - E_{F\sigma} - eV)} + 1)$ and $f_R(\epsilon) = 1/(e^{\beta(\epsilon - E_{F\sigma})} + 1)$ with $E_{F\sigma}$ being the Fermi energy of the electrodes. Hereafter, we apply this expression to simple cases. First we assume that $\Sigma^{r,a}_{mn\sigma}(\epsilon) = \delta_{mn}\Sigma^{r,a\sigma}_n$. This corresponds to a situation in which energy levels in the island are mutually uncorrelated during the tunneling process. Then all Green's functions are diagonalized and $A_{n_1n_2\sigma}(\epsilon)$ reduces to

$$A_{n\sigma}(\epsilon) = \frac{\hbar\Gamma_{n\sigma}(\epsilon)}{[\epsilon - (E_{n\sigma} + V_{d\sigma}) - \Lambda_{n\sigma}(\epsilon)]^2 + [\Gamma_{n\sigma}(\epsilon)]^2/4}. \tag{16}$$

and $\Theta_{n\sigma}(\epsilon)$ reduces to $\Gamma_{n\sigma}(\epsilon)^{-1}$.

$\Gamma_{nn'\sigma}(\epsilon)$ is related with the density of state (DOS) of the electrode such that

$$\Gamma_{nn'\alpha\sigma}(\epsilon) = \sum_{\mathbf{k}} V^*_{n\mathbf{k}\alpha\sigma}V_{n'\mathbf{k}\alpha\sigma}\delta(\epsilon - E_{\mathbf{k}\alpha\sigma})$$
$$\approx \mathcal{V}\int\frac{4\pi k^2 dk}{(2\pi)^3}V^*_{n\mathbf{k}_F\alpha\sigma}V_{n'\mathbf{k}_F\alpha\sigma}\delta(\epsilon - E_{\mathbf{k}\alpha\sigma})$$
$$= V^*_{n\mathbf{k}_F\alpha\sigma}V_{n'\mathbf{k}_F\alpha\sigma}D_{\alpha\sigma}(\epsilon), \tag{17}$$

where $D_{\alpha\sigma}(E)$ is a density of state expressed by $D_{\alpha\sigma}(E) = \frac{\mathcal{V}}{4\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}\sqrt{E+\sigma h_\alpha}$ in a three-dimensional space. This approximation will be most suitable when the interfacial material is a quantum box or particles. From the relation $\Gamma_{\alpha\sigma}(\epsilon) = 2\pi D_{\alpha\sigma}(\epsilon)|V_{\mathbf{k}\alpha\sigma}|^2$, resistances $R_{\alpha\sigma}(\alpha = L, R)$ can be evaluated to be $R_{\alpha\sigma}/R_K = (\Gamma_{\alpha\sigma}(E_{F\sigma})D_d(E_{F\sigma}))^{-1}$, where R_K is the resistance quantum h/e^2 =25.8kΩ and $D_d(E_{F\sigma})$ is the DOS of the island at the Fermi energy. In this paper MR is discussed in terms of the change of $\Gamma_{\alpha\sigma}$ instead of $R_{\alpha\sigma}$

We see $\Gamma_{n\alpha\sigma}(E_{\mathbf{k}\alpha\sigma})$ as a function of the internal magnetic field : $\Gamma_{n\alpha\sigma}(E_{\mathbf{k}\alpha\sigma}) \equiv \Gamma_{n\alpha\sigma}(h_\alpha)$. Thus we have the resonant tunneling formula [9] under an external magnetic field, H, as,

$$J_L(H) = \frac{e}{2\pi\hbar}\sum_{n\sigma}\int_{s_0}^{\infty} dE_{\mathbf{k}L\sigma}\frac{\Gamma_{nL\sigma}(h_L)\Gamma_{nR\sigma}(h_R)}{[E_{\mathbf{k}L\sigma}-(E_{n\sigma}+V_{d\sigma})]^2+\left[\frac{\Gamma_{nL\sigma}(h_L)+\Gamma_{nR\sigma}(h_R)}{2}\right]^2}\{f_L(E_{\mathbf{k}L\sigma})-f_R(E_{\mathbf{k}L\sigma})\}, \tag{18}$$

where $s_0 = \max(eV - \sigma h_L, -\sigma h_R)$.

Here we compare the MR of the resonant tunneling current with that of the single junction by their conductances. The conductance of the system is given by $G_\sigma \equiv \partial J_\sigma/\partial V$, and the magnetoresistance is defined as

$$\begin{aligned} MR &\equiv \frac{G_{\uparrow\uparrow}-G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}} \\ &= \frac{\sum_\sigma(G_\sigma(H)-G_\sigma(-H))}{\sum_\sigma G_\sigma(-H)}. \end{aligned} \tag{19}$$

We have a picture that the change of magnetic field makes the distribution of the DOS (Fig.1) and the $\Gamma_{\alpha\sigma}(h_\alpha)$ (Eq.(17)). We consider the derivation of $\Gamma_{\alpha\sigma}(h_\alpha)$ from the case where the internal magnetic field is zero, $h_\alpha = 0$:

$$\begin{aligned} \Gamma_{nL\sigma}(h_L) &= \Gamma_{nL\sigma}(0)(1+\Delta_{L\sigma}(h_L)), \\ \Gamma_{nR\sigma}(h_R) &= \Gamma_{nR\sigma}(0)(1+\Delta_{R\sigma}(h_R)), \\ E_{n\sigma}(h_n) &= E_{n\sigma}(0)(1+\gamma_\sigma(h_n)), \end{aligned} \tag{20}$$

where $|\Delta_{\alpha\sigma}(h_\alpha)| \ll 1$ (α=L, R) and $|\gamma_\sigma(h_n)| \ll 1$ and we set $\Gamma_{n\alpha\sigma}(0) = \Gamma_{n\alpha}$ and $E_{n\sigma}(0) = E_n$ in the following. Note that $\gamma_\sigma(h_n)$ depends on the relative displacement of the energy-level

compared with the two electrodes. The spin polarized current through the single junction, $J_\sigma^{(S)}(H)$ at $\alpha{=}L$ is given from Eq.(9) with $n, m \to \mathbf{k'}_R$ and $G_{nm\sigma}^{><}(t) \to g_{\mathbf{k'}_R\sigma}^{><}(t)$ as

$$J_\sigma^{(S)}(H) = \frac{e}{2\pi\hbar}\int_{s_0}^{\infty} dE_{\mathbf{k}L\sigma}\Gamma_{LR\sigma}(h_L)D_{R\sigma}(h_R)$$
$$\times\{f_L(E_{\mathbf{k}L\sigma}) - f_R(E_{\mathbf{k}L\sigma})\}, \tag{21}$$

and the conductance $G_\sigma^{(S)}(H)$ is expressed as $G_\sigma^{(S)}(H) \equiv \Gamma_{L\sigma}(h_L)D_{R\sigma}(h_R)$ ($\sim |V_{\sigma\mathbf{k}_F}|^2 D_{L\sigma}(h_L)D_{R\sigma}(h_R)$). We consider the case where the left electrode is a soft magnet and the right one is a hard magnet. Then $\Delta_{R\sigma}(h_R)$ does not change under the inversion of the external magnetic field H, and the MR of the single junction is given by

$$MR^{(S)} = \sum_\sigma \frac{1}{2}(\Delta_{L\sigma}(h_L) - \Delta_{L\sigma}(-h_L)). \tag{22}$$

Next we derive the MR of the double barrier structure. Conductance $G_{n\sigma}$ near the n-th energy-level in the island is given by using $\partial f(\epsilon)/\partial\epsilon = -\delta(\epsilon-\mu)$ $(T\to 0)$ in Eq.(18) :

$$G_{n\sigma}(H) \approx \frac{e^2}{2\pi\hbar}\frac{\Gamma_{nL\sigma}(h_L)\Gamma_{nR\sigma}(h_R)}{[E_F - E_{n\sigma}(h_n)]^2 + \left[\frac{\Gamma_{nL\sigma}(h_L)+\Gamma_{nR\sigma}(h_R)}{2}\right]^2}. \tag{23}$$

From this we obtain the conductance at the peak current (current at resonance) $G_{n\sigma}^{\rm res}(H)$ and that at the valley current (current at off-resonance) $G_{n\sigma}^{\rm off}(H)$:

$$G_{n\sigma}^{\rm res}(H) \approx \frac{2e^2}{\pi\hbar}\frac{\Gamma_{nL\sigma}(h_L)\Gamma_{nR\sigma}(h_R)}{[\Gamma_{nL\sigma}(h_L) + \Gamma_{nR\sigma}(h_R)]^2}, \tag{24}$$

$$G_{n\sigma}^{\rm off}(H) \approx \frac{e^2}{2\pi\hbar}\frac{\Gamma_{nL\sigma}(h_L)\Gamma_{nR\sigma}(h_R)}{[E_F - E_{n\sigma}(h_n)]^2}. \tag{25}$$

Here we assume that $E_F - E_{n\sigma}(h_n) > 0$. The change of the conductances Eq.(24) and Eq.(25) are given in order of $\Delta_{L\sigma}(h_L)$ as

$$G_{n\sigma}^{\rm res}(H) - G_{n\sigma}^{\rm res(0)}$$
$$\approx \sum_\sigma \frac{2e^2}{\pi\hbar}\frac{\Gamma_{nL}\Gamma_{nR}}{[\Gamma_{nL}+\Gamma_{nR}]^3}(\Gamma_{nR}-\Gamma_{nL})\Delta_{L\sigma}(h_L), \tag{26}$$
$$G_{n\sigma}^{\rm off}(H) - G_{n\sigma}^{\rm off(0)}$$
$$\approx \sum_\sigma \frac{e^2}{2\pi\hbar}\frac{\Gamma_{nL}\Gamma_{nR}}{[E_F-E_{n\sigma}]^2}\left[\Delta_{L\sigma}(h_L) + \frac{2E_{n\sigma}}{E_F-E_{n\sigma}}\gamma_\sigma(h_n)\right]. \tag{27}$$

where $G_{n\sigma}^{\mathrm{res}(0)}$ and $G_{n\sigma}^{\mathrm{off}(0)}$ are values when there is no internal magnetic field.

Thus MR of the resonant current and off-resonant current are given as

$$MR_n^{\mathrm{res}}=\sum_\sigma \frac{1}{2}\frac{\Gamma_{nR}-\Gamma_{nL}}{\Gamma_{nR}+\Gamma_{nL}}(\Delta_{L\sigma}(h_L)-\Delta_{L\sigma}(-h_L)), \tag{28}$$

$$\begin{aligned}MR_n^{\mathrm{off}}=&\sum_\sigma \frac{1}{2}[\Delta_{L\sigma}(h_L)-\Delta_{L\sigma}(-h_L)\\ &+\frac{2E_{n\sigma}}{E_F-E_{n\sigma}}(\gamma_\sigma(h_n)-\gamma_\sigma(-h_n))].\end{aligned} \tag{29}$$

Because of the factor $(\Gamma_{nR}-\Gamma_{nL})/(\Gamma_{nR}+\Gamma_{nL})<1$, Eq.(28) shows that the ratio of MR of the peak current is smaller than that of the single junction (Eq.(22)), whereas Eq.(29) shows that the MR of the valley current is enhanced depending on the change of the energy-level in the island (*i.e.* if $\gamma_\sigma(h_n)$ - $\gamma_\sigma(-h_n)$ has the same sign as $\Delta_{L\sigma}(h_L)$ - $\Delta_{L\sigma}(-h_L)$). In the later numerical calculations, the enhancement of the valley current is shown as the simplest case where the island is non-magnetic material. Thus the MR enhancement of more than 90% of the double junction shown by Zhang [5] is found to be the enhancement of the valley current and NOT that of the peak current. From these results, it is easy to conjecture the PV ratio, defined $PV_n(H)\equiv\sum_\sigma G_{n\sigma}^{\mathrm{res}}(H)\,/\sum_\sigma G_{n\sigma}^{\mathrm{off}}(H)$, decreases. The explicit expression of the PV ratio in changing the external magnetic field is given as

$$\begin{aligned}PV_n(H)-PV_n(-H)&=\frac{\sum_\sigma G_{n\sigma}^{\mathrm{res}}(H)}{\sum_\sigma G_{n\sigma}^{\mathrm{off}}(H)}-\frac{\sum_\sigma G_{n\sigma}^{\mathrm{res}}(-H)}{\sum_\sigma G_{n\sigma}^{\mathrm{off}}(-H)}\\ &\approx -PV_n(0)\sum_\sigma(\frac{\Gamma_{nL}}{\Gamma_{nR}+\Gamma_{nL}}(\Delta_{L\sigma}(h_L)-\Delta_{L\sigma}(-h_L))\\ &+\frac{E_{n\sigma}}{E_F-E_{n\sigma}}(\gamma_\sigma(h_n)-\gamma_\sigma(-h_n))).\end{aligned} \tag{30}$$

This shows that PV ratio is reduced when the junction conductance increases under the change of the direction of the external magnetic field.

Although these results are derived starting from Eq. (20), they are also valid for a one band model where $\Gamma_{nR\uparrow}\gg\Gamma_{nR\downarrow}$ and only one polarized spin current exists. In this case, all equations are similarly obtained without summation with σ and the factor 1/2.

In our formulation the resonant level is assumed to be due to a quantum dot such as a small magnetic particle, however, the equations derived above are general forms and the

results obtained here are considered to be intrinsic to the resonant tunneling phenomenon such as in thin film systems [10].

III. RESULTS AND DISCUSSIONS

Here we show the numerical results obtained from Eq.(18). The current-voltage characteristics through a double barrier structure reflect the effect of DOS of the electrodes and the magnitude of the Fermi surface [11]. The form of the I-V curve has a peak when the Fermi energy fits the discrete energy-level and becomes lower as the bias voltage becomes higher in the three-dimensional electrode. The width of the peak current shows the magnitude of the Fermi energy when the discrete energy-level passes through the Fermi energy of the electrode. The existence of an internal magnetic field makes the DOS of up spins and that of down spins different, and the I-V curve shows a dip reflecting these two different DOS at the Fermi energy. These features of the model are represented in Fig. 2 which shows the I-V curve and $MR = (J_{\uparrow\uparrow} - J_{\uparrow\downarrow})/J_{\uparrow\downarrow}$ of a resonant tunneling structure (Eq.(18)) with that of a single junction (Eq.(21)) as a function of applied bias voltage when there is a non-magnetic single energy-level in an island and the left electrode changes its internal magnetic field. In $J_{\uparrow\uparrow}$, we take h_L =1.8 eV, h_R=2.1eV and $J_{\uparrow\downarrow}$, h_L =-1.8 eV, h_R=2.1eV for $E_F = 3$eV. Here we assume $\Gamma_{\alpha\sigma}(\epsilon) = \sqrt{\epsilon/E_{F\sigma}}\Gamma_{\alpha 1}(\epsilon)$ for the energy dependence of the three-dimensional DOS of the electrodes on the I-V characteristics(Fig.1). To be more realistic, we take $\Gamma_{\alpha 1}(\epsilon)$ $= \Gamma_{\alpha 0}C^{(\epsilon/E_F)}$ with constant $\Gamma_{\alpha 0}$ and C . This is an extended form used in Ref. [12] and shows that the electron with higher energy has higher tunneling probability. As discussed above, the peak current is reduced more than the current of the single junction, whereas the off-resonant peak current is greatly enhanced, that is, more than 60%. We can obtain the same relation between the $MR^{(S)}$ and $MR^{(D)}$ even in the case where $C = 1$.

The above results can also be applied to the MR of a leak tunneling current via an impurity trap state in the single junction [13]. In this case our results show that the MR of the leak current is less than that without a trap state and it is not necessary to take care of

the effect of the leak current in the measuring process of MR.

IV. CONCLUSIONS

In conclusion, we have studied the MR of the resonant tunneling through a double-barrier system by using the Keldysh formulation. Although our model is simpler than that of the S-matrix method by Zhang *et al.* [5], it can describe the intrinsic characteristics of the resonant tunneling current which the S-matrix theory cannot treat easily. We showed that the peak current is not enhanced by the change of the magnetization of the soft magnet whereas the valley current is greatly enhanced when compared with the current in a single junction. We also found that the PV ratio decreases when the junction conductance increases.

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FIGURES

FIG. 1. (a) Schematic band-edge diagram for a double barrier structure. At sufficiently low temperature, the tunneling of electrons takes place when the discrete energy-level passes through the corresponding Fermi energy band. (b) Density of state of the up spin electron and down spin electrons at the electrode $\alpha(\alpha = L, R)$. h_α is an internal magnetic field.

FIG. 2. Resonant tunneling current and the MR (see text) in the case where the left electrode is a soft magnet. $MR^{(D)}$ is the MR of the double barrier resonant tunneling current and $MR^{(S)}$ is that of the single barrier. In $J_{\uparrow\uparrow}$, $h_L/E_F = 0.6$ and $h_R/E_F = 0.7$ and in $J_{\uparrow\downarrow}$, $h_L/E_F = -0.6$ and $h_R/E_F = 0.7$ for E_F= 3.0eV where $T/E_F = 10^{-3}$, Γ_{L0}/E_F=5.0×10^{-5}, Γ_{R0}/E_F=2.5×10^{-5} and $C = 10$ (see text). The $MR^{(D)}$ and $MR^{(S)}$ refer to the right scale and the $J_{\uparrow\uparrow}$ and $J_{\uparrow\downarrow}$ refer to the left one. $MR^{(D)}$ at the peak current is smaller than $MR^{(S)}$, whereas that at the valley current is enhanced more than 60%.